

# ORKA: A Precision Measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at Fermilab

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## 1 Introduction

The decay  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  is highly suppressed in the Standard Model (SM) and occurs through the diagrams in Figure 1. Several factors make this decay “theoretically

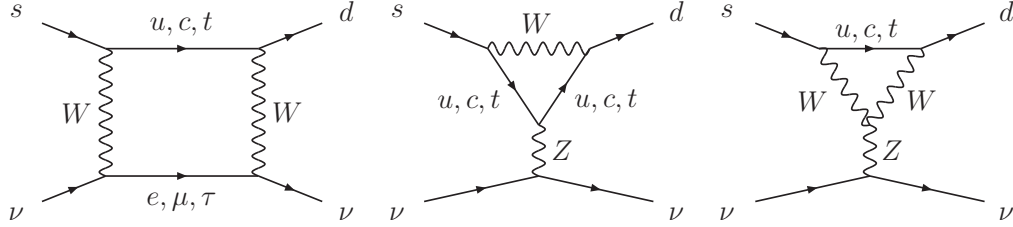


Figure 1: Electroweak loop diagrams responsible for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ .

clean.” In the usual operator product expansion treatment, a single effective operator is relevant. Loops involving the top quark dominate. The hadronic current is known from the well-measured  $K_L^0 \rightarrow \pi^+ e^- \bar{\nu}$  decay. In fact, the dominant uncertainties on the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  branching fraction in the SM result from uncertainties on CKM elements, which will be reduced over time. The current SM expectation [1] is

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (7.8 \pm 0.8) \times 10^{-11}.$$

Significantly, this decay remains clean in most extensions of the SM, and many new physics scenarios can lead to deviations from the SM expectation by at least a factor of two. Figure 2 shows expected branching fractions in a few new physics scenarios.

The  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay was observed by the Brookhaven experiments E787 and E949, which ran at the Alternating Gradient Synchrotron. E949 was an upgrade

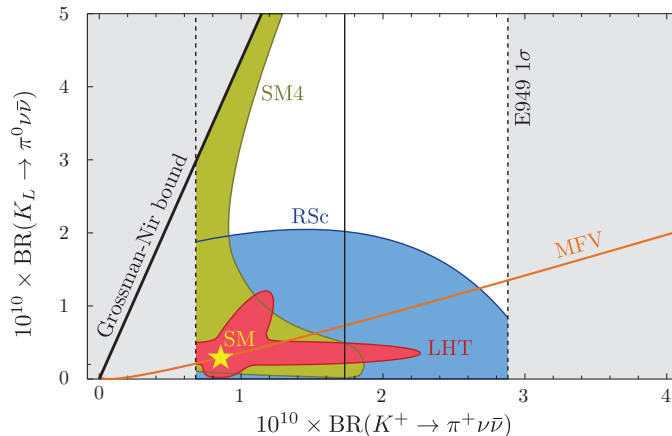


Figure 2: Predictions from various models for the branching fractions of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  and  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ . The yellow star shows the SM predictions. The red region is allowed by Littlest Higgs models with T-violation (LHT). The blue region is preferred by the Randall-Sundrum model with custodial protection (RSc). The olive region is preferred by the Standard Model with a fourth sequential generation (SM4). The orange line shows the constraint imposed by minimal flavor violation (MFV). The vertical dashed lines show the  $\pm 1\sigma$  region from the BNL E787/E949  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  measurement. The figure is reproduced from Reference 2.

to the earlier E787, using the same separated  $K^+$  beamline and much of the same detector. The experiment used the stopped- $K^+$  technique. E787/E949 observed [3] seven signal events and reported a branching fraction measurement:

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.73_{-1.05}^{+1.15} \times 10^{-10}.$$

A new experiment is being prepared at CERN, NA62, which will take data in the next few years in parallel with LHC running. NA62 builds upon a well-established kaon physics program (NA31, NA48) and expects to be able to collect about 100  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  events. NA62 will be the first experiment to apply the decay-in-flight approach to the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay. NA62 is described in another contribution to CKM2012.

The ORKA experiment has been proposed [4] at Fermilab to extend the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  reach to the 1000 event level. This will provide a powerful test for new physics.

## 2 The ORKA Experiment

The basic concept of ORKA is to apply the method and techniques that were demonstrated in BNL E787/E949. ORKA does not require better background rejection

than E949 achieved. ORKA will use existing facilities at Fermilab, including detector infrastructure and a superconducting solenoid (from CDF) to moderate costs. ORKA will be a fully state-of-the-art detector, which will lead to substantial gains compared to E949 in performance and data-acquisition capability.

The signature for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  is a single  $\pi^+$  with no associated particles. The major backgrounds are the decays  $K^+ \rightarrow \pi^+ \pi^0$ , where both  $\gamma$ 's from the  $\pi^0$  are missed, and  $K^+ \rightarrow \mu^+ \nu$ , where the muon is misidentified as a pion. The backgrounds are suppressed by a hermetic photon veto system and extremely strong  $\pi^+$  identification from observing the full decay chain  $\pi \rightarrow \mu \rightarrow e$ . Figure 3 shows the  $\pi^+$  (or  $\mu^+$ ) momentum in the  $K^+$  rest frame, which is the lab frame of the experiment since beam  $K^+$ 's are stopped at the center of the detector in an active scintillating fiber stopping-target. The experiment is sensitive to  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  events in two signal

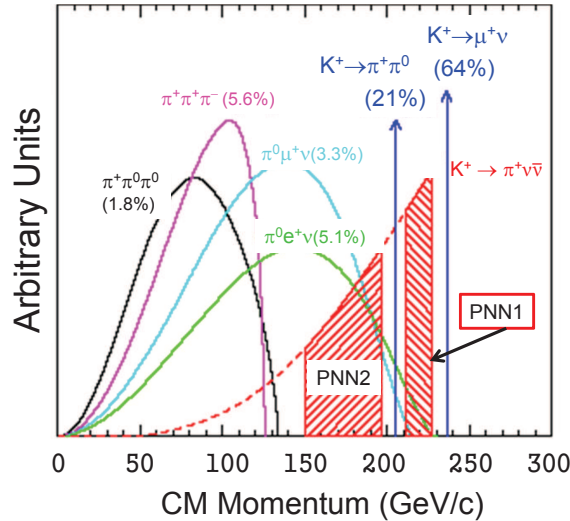


Figure 3: Charged particle momentum for the signal and background decays. Values in parentheses represent the branching fractions of the decay modes. The regions indicated as PNN1 and PNN2 are signal regions used in the experiment.

regions, PNN1 between the  $K^+ \rightarrow \pi^+ \pi^0$  and  $K^+ \rightarrow \mu^+ \nu$  peaks seen in Figure 3, and PNN2 below the  $K^+ \rightarrow \pi^+ \pi^0$  peak. With a high-statistics event sample, ORKA will measure not only the branching fraction but will also be sensitive to the effects of possible scalar or tensor interactions on the  $\pi^+$  spectrum.

The  $K^+$  beam for ORKA will be produced by 95 GeV protons from the Fermilab Main Injector, extracted over a 4.4 s spill every 10 s, providing a beam power of about 75 kW. This is an increase of almost a factor of two over the beam power for E949, and it provides about  $9 \times 10^7$   $K^+$ /spill into the acceptance of the secondary beamline. The separated secondary beam will deliver a  $K^+/\pi^+$  ratio of about three. By running

at lower momentum than the BNL experiment (600 MeV vs 710 MeV), the fraction of the  $K^+$ 's stopped in the active stopping-target will more than double. When all anticipated beam changes are accounted for, ORKA will sample about a factor of seven more stopped- $K^+$  decays per second than E949.

The ORKA detector is shown in Figure 4. While modeled after E787/E949, all detector components will be new. Large performance gains will come from several sources. A larger magnetic field (1.0 T  $\rightarrow$  1.25 T) will improve momentum resolution.

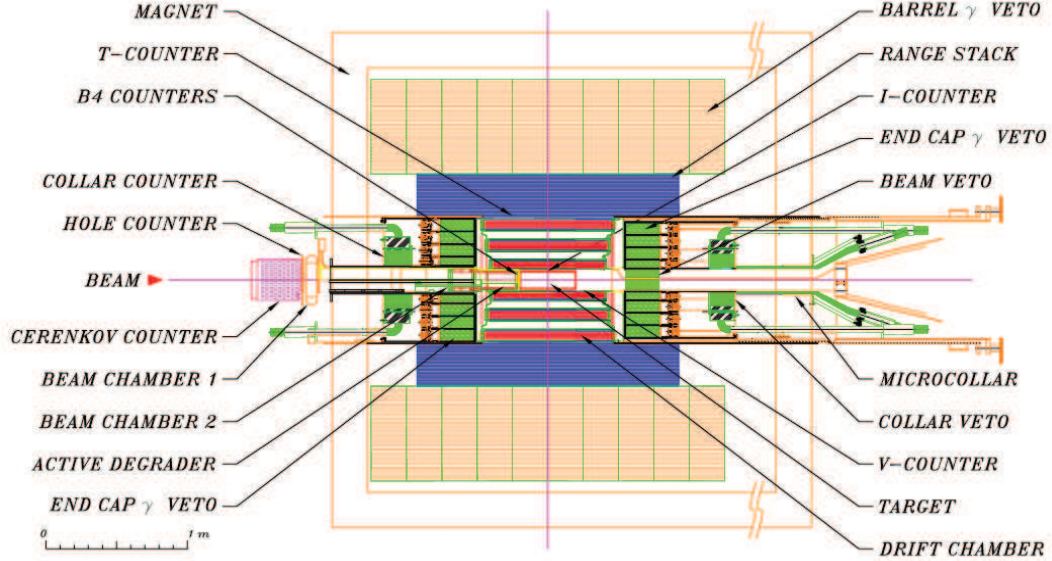


Figure 4: Elevation view of the proposed ORKA detector. Beam enters from the left.

A longer drift chamber will increase geometrical acceptance. An improved scintillating fiber stopping-target with smaller fibers and better light collection will improve  $K:\pi$  separation and improve vertex resolution. A thicker ( $17X_0 \rightarrow 23X_0$ ) photon veto system will improve  $\pi^0$  rejection. Waveform digitizers (500 MHz, 10-bit) on all scintillators without multiplexing will reduce sensitivity to accidentals. A modern “triggerless” data-acquisition system will eliminate deadtime. Extrapolations from E949 experience show a net gain in acceptance of a factor of about 11 over E949, while maintaining as good or better background rejection.

In 5000 hours of running per year, ORKA will collect about 210  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  events per year if the branching fraction is at the SM level. The expected branching fraction uncertainty versus time is shown in Figure 5 assuming the same signal/background ratio achieved in E949. The experimental uncertainty reaches the expected theory uncertainty after a few years of running. In addition, ORKA will be able to make improvements in the measurement of several other  $K^+$  decay modes.

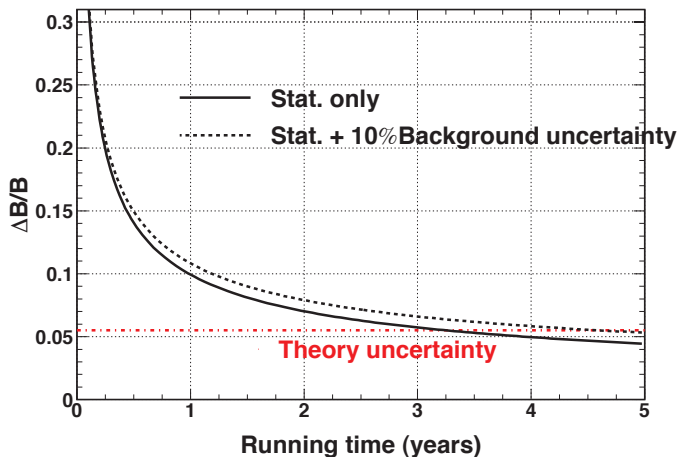


Figure 5: Fractional  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  branching fraction uncertainty versus running time. Solid (dashed) curve is the sensitivity for no (10%) background uncertainty. The red (dot-dashed) line is the theory uncertainty excluding uncertainties on CKM elements.

### 3 ORKA Status

ORKA received Stage-1 approval from Fermilab in December, 2011, and is conducting in R&D in advance of DOE approval. A schedule with data taking early in 2017 is technically possible, but is contingent on funding. The ORKA Collaboration<sup>1</sup> is very motivated, active, and hopeful that this experiment will proceed in a timely way.

## References

- [1] J. Brod, M. Gorbahn, and E. Stamou, Phys. Rev. D **83**, 034030 (2011).
- [2] D. M. Straub, “New physics correlations in rare decays,” talk presented CKM2010, Warwick, UK, (September 6-10, 2010), arXiv:1012.3893 [hep-ph].
- [3] A.V. Artamonov *et al.*, Phys. Rev. D **79**, 092004 (2009).
- [4] <http://projects-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1365>

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<sup>1</sup>The ORKA Collaboration consists of groups from Arizona State University, University of British Columbia, Brookhaven National Lab, Fermilab, University of Illinois at Urbana-Champaign, INFN-Pisa, INFN-Napoli, INR-Moscow, JINR (Russia), University of Mississippi, Notre Dame, University of Northern British Columbia, Universidad Nacional Autonoma de Mexico, Universidad Autonoma de San Luis Potosi (Mexico), University of Texas at Arlington, University of Texas at Austin, TRIUMF, and Tsinghua University (China).